Advancements and Challenges in Hybrid Electric Vehicles: Comprehensive Analysis of Configurations and its Future Prospects

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Abstract: *Environmental concerns and diminishing fuel reserves are influencing a shift away from traditional combustion engine vehicles towards Hybrid Electric Vehicles (HEVs). The performance of HEVs is closely linked to their design and components, which include the internal combustion engine (ICE), various energy storage systems (ESS), electric motors, bidirectional converters, and ultra-capacitors. The paper explores various configurations of HEVs, highlighting how different designs cater to diverse operational needs and efficiency standards. The review also addresses the current challenges faced by the HEV industry by exploring the work done by various researchers in this field. These include issues related to battery life, infrastructure development, cost-effectiveness, and consumer acceptance. The paper also examines potential solutions and ongoing research aimed at overcoming these obstacles.*

Keywords: *Hybrid Electric Vehicle, ICE, Battery, State of Charge (SOC), ESS.*

I. INTRODUCTION

Hazardous emissions and greenhouse gases (GHGs) are the side products of the combustion of fossil fuels for energy needs. The emission of GHG is the major cause of rapid climate change, such as global warming and the melting of polar ice. The GHGs are mainly comprised of CO2, NOx, CO, and methane [1]-[5]. Fig. 1 shows the emission of GHG from various usage sectors and shows that transportation shares almost 14%. Worldwide development and expansion of numerous urban areas have substantially increased the number of vehicles on the road. Of course, this high percentage of transportation GHG is due to the vehicle's internal combustion engine (ICE)[6][7]. Therefore, the decarburization of transportation will eliminate the CO2 emissions of the transportation sector. This has motivated modern efforts to replace ICE-based vehicles with alternative power plants that are sustainable and clean. Electrifying transportation is one promising approach to solve the above health and environmental problems. Thus, electric vehicles (EVs) have been viewed as a substitute for ICE vehicles[8]. The EV offers the possibility of zero vehicle emissions, lower lifetime cost, enhanced safety, and possible renewable energy. However, the present EV technology is associated with the problems of limited range, high initial cost, and longer recharge time compared with the ICE vehicles[9]-[11]. The limited range of EVs may not pose a problem in many metropolitan areas and developing countries. However, the present lack of necessary fast-charging stations poses a barrier to entry even in these suitable areas[12]-[15].

EV is a road vehicle which involves with electric propulsion. EV can be classified into three types: pure electric vehicles (PEVs)[16], hybrid electric vehicles (HEVs)[17][18], and fuel cell electric vehicles (FCEVs)[19] as shown in table-1. Today, they are in different stages of development due to existing technology, the major characteristics and features of three types of EV as shown in Table 1. We can see that electric motor drives technique, in which the field-oriented control (FOC) and variable-voltage variable frequency (VVVF) are adapted widely, is the common technique in EV. The battery initial cost and battery management create bottleneck in PEVs in spite of zero emission; these two barriers cannot be solved in the near future, so the HEV is the interim solution before the full commercialization of PEV when there is a breakthrough in battery initial cost and management. FCEV has long-term potential for future main stream vehicles [20], however the technology of its cost and refueling system is still in early development stage [21], thus this paper mainly discusses HEV.

Table-1 Types of EV with their Characteristics:

Type of electric Vehicle	**Pure EV**	**Hybrid EV**	**Fuel- Cell based EV**
BESS(Battery/Energy Storage System)	• Battery	• Battery, • Ultra-capacitor, ICE	• Fuel Cell
Propulsion Technique	• EM	• EM, ICE	• EM
Characteristics and Feature	• Zero Emission • Short Driving Range	• Lower Emission • Longer Range • Complex System	• Zero Emission • Higher Initial Costs • Medium Driving Range

	• Higher Initial Costs • Independent of fossil fuel • Commercially available	• Higher cost than ICE • Commercially available but room for advancement	• Under development • Higher cost
Major Techniques	• EM control • BM • Charging device	• EM control • BM • Managing multiple energy sources and optimal system efficiency • Component sizing	• Fuel Processor • Fueling System • Fuel Cell cost
Regenerative Braking	• Available	• Available	• Available
Energy Source Infrastructure	• Electrical Grid Charging Facilities	• Electrical grid charging facility (for plug-in EV)	• Gasoline station
Major Issue	• Battery sizing • Lower range • Charging facilities • Battery lifetime	• Battery sizing and management • Control and Optimization management of multiple resources • cost	• Fuel cell cost • Lifecycle • Reliability • Hydrogen production • Costing

The HEV technology can be developed to overcome the aforementioned shortcomings of both ICE vehicles and EVs. The HEV combines the ICE with a battery-powered electric motor (EM), combining the advantages of both for transportation. These include low emissions, high reliability, high fuel efficiency, and long range compared with the ICE or EVs. Furthermore, the HEV can still recover the braking vehicle kinetic energy, as in the EV. However, the HEV powertrain is more complex compared to the EV or the ICE vehicle [21]-[23]. This complexity stems from its components and controls. This article presents an overview of the important components utilized in the HEV powertrain, as well as their architectures, energy management strategies (EMSs), choice of power electronic converters, hybrid energy storage systems (HESSs), and traction motors[24][25].

Fig. 1 depicts a system-level design procedure for a high efficiency HEV powertrain. The key levels in an HEV consist of Controllers, Electric Motor, Management devices, best suited topologies etc. These component can be categorized into three levels:

1. Configuration of EV
2. Energy Storage System
3. Energy Management system

The first level is the selection of the architecture. There are four major types of powertrain topologies: series, parallel, series–parallel, and complex. This selection plays a pivotal role in designing an efficient powertrain. Details of HEV topology are presented in Section III. The second level determines the required advanced technology components and their ratings to be integrated into the powertrain discussed in Section- IV. This level includes the choice of the energy storage system (ESS), EM, Ultra-Capacitors and dc–dc/dc–ac converters.

The third stage is the selection of the EMS. This is a very crucial aspect as it is responsible for maintaining the operation of each component, and the overall system, in their most energy-efficient region discussed in Section-V. For example, the EMS is responsible for splitting the power demand between the electrical and mechanical power plants, with the consideration of their efficient operating regions and their various constraints. A well-designed EMS can significantly improve the powertrain fuel economy while maintaining battery health and reducing tailpipe emissions. The EMS adopted should consider the various objectives and constraints so that the design goals can be achieved.

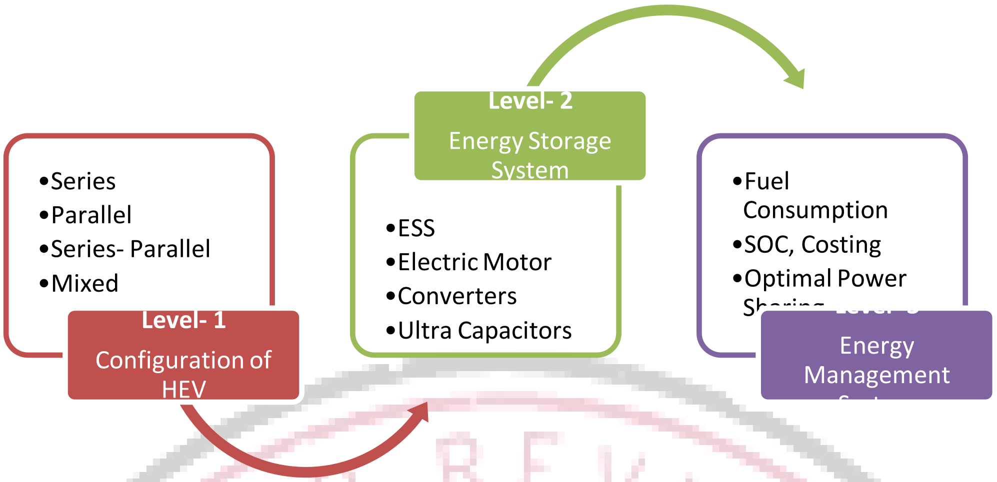

Figure-1 System-level design procedure for an HEV for a detailed Review

II. NEED AND WORKING OF HEV

As stated by a survey, world population will reach to 10 billion in 2050 and thus escalating the automobiles to 2.5 billion provoking the greenhouse effect [26]According to an estimation, in year 2037 the limited petroleum available to us will run out and 400 million cars will become useless as the supply of gasoline will become extremely expensive [27]. Typical automobiles use internal combustion engine (ICE) along with gasoline ingestion resulting in hazardous gases that grounds for ecofriendly deprivation, greenhouse effect and bad human health. For this purpose, automobile engineering experts are giving it all to produce vehicles that can run on other sources. In this day and age, modern cities significantly claim the importance on green technology. With the reliance on overseas oil and growing oil rates, excessive intake of fossil fuels and the necessity of reduction in greenhouse gas emissions to save the environment have given enough incentives for the trade and deployment of hybrid electric vehicles (HEV) [28].

HEV is an environment friendly fuel efficient automobile which goes uncontaminated with less tailpipe emissions and improved traveling distance fulfilling ecological legislations. HEV can dampen the impact of growing oil rates and recover fuel economy devoid of losing the performance, consistency and protection of the car which is exactly the need of current age. Usually, an HEV is preferred over a conventional automobile due to its charge sustaining mode whose performance relies on regenerative breaking and small fuel engine size. The mechanism doesn’t initiates the vehicle but works at optimum conditions when geared.

There are numerous techniques by which HEVs can reduce energy intake. Some avail efficiency improving method for instance regenerative braking. Some use motor-generator combination. Some use the recognized start-stop system [29]. In HEV, mechanical energy is transformed into electrical energy and vice versa unlike conventional vehicles. A surplus of electric charge is stored in a battery to create mechanical energy when desired. The performance of HEV is significantly determined by its construction and modules. The core modules include internal combustion engine (ICE), single or multiple energy storage system (ESS), electric motor, bidirectional converters and control unit. Working of hybrid electric vehicle is categorized into 3 processes:

1) Some use the recognized start-stop system i.e. diminish idle emissions by shutting down the engine when not required and resuming it when desired which can offer a very uniform start to vehicle.
2) Under deceleration or braking, Hybrid energy storage system aims at regenerative braking, which charges the battery by transforming kinetic energy into electric energy, instead of radiating it as heat energy.
3) Some use their internal combustion engine to produce electrical energy by energy efficient dual powertrain of engine/motor i.e. rotating a generator. The power produced is used to either drive the vehicle (directly command the plug-in motors) or to restore the charge on batteries. Through this phenomenon, energy is passed to the external lane with negligible loss [30].

II. LEVEL-1 HEV CONFIGURATIONS

A hybrid electric vehicle (HEV) is a vehicle which is using two sources of energy for propulsion, one of them being electrical energy. Most of the road vehicles with hybrid powertrain use an internal combustion engine (ICE) combined with an electric machine (EM). Compared with a conventional vehicle, powered by an ICE, a hybrid electric vehicle is capable of performing these functions:

- Fast ICE stop & start
- Energy recuperation during braking (regenerative braking)
- Torque assist/boost
- Electric driving

- Coasting (optional)

The type of HEV is determined by how the powertrain propels the vehicle down the road and may be considered either series, parallel, or series-parallel. The first configuration is Series HEV[31]. A series hybrid is like a battery electric vehicle (BEV) in design. Here, the combustion engine drives an electric generator instead of directly driving the wheels. The generator both charges a battery and powers an electric motor that moves the vehicle. When large amounts of power are required, the motor draws electricity from both the battery and the generator[32]. Series hybrids may also be referred to as extended-range electric vehicles (EREVs) or range-extended electric vehicles (REEVs) since the gas engine only generates electricity to be used by the electric motor and never directly drives the wheels. Modern examples include the Cadillac ELR, Chevrolet Volt, and Fisker Karma, general example in which this are used is plug in EV[33][34].

For proper energy management strategies (EMSs) with broad adaptability for series hybrid electric vehicles (HEVs). this paper in [35] utilizes deep reinforcement learning (DRL) to develop EMSs for a series HEV. The proposed method is systematically introduced from offline training to online applications. Simulation results achieves an average 3.5% gap from benchmark, superior to MPC-based EMS with accurate prediction; after further applying output frequency adjustment, a mean gap of 8.7%, which is comparable with MPC-based EMS with mean prediction error of 1 m/s, is maintained with concurrently noteworthy improvement in reducing engine start times. Besides, its impressive computation speed of about 0.001 s per simulation step proves its practical application potential, and this method is independent of powertrain topology such that it is applicative for any type of HEVs even when future driving information is unavailable.

Another study in [36] proposes fuel-saving potential on series hybrid electric vehicles on MATLAB/Simulink software and multi objective evolutionary optimization using Genetic Algorithm. Result shows that the method proposed have reduced rates of fuel consumption and nitric oxide are decreased by up to 12.48% and 92.64%, respectively. Besides, all these will provide theoretical basis and digital model support for the development of efficient and energy-saving new energy vehicles.

Another paper in [37] proposes a modified hybrid electric vehicle powertrain system that addresses the shortcomings of a series hybrid electric vehicle powertrain. Result analysis during initial parameterization showed a reduction in gross vehicle weight of the proposed configuration by 244 kg (1.5%) and an improvement in the average operating efficiency of the traction motor by around 11%, when compared to a series hybrid electric vehicle. Furthermore, the optimization results for the proposed configuration established an improvement in the fuel economy by 21% while meeting vehicle performance requirements.

Significant research efforts have been invested in the automotive industry on hybrid electrified powertrains in order to reduce the dependence of passenger cars on oil. Electrification of powertrains resulted in a wide range of hybrid vehicle architectures. The fuel consumption of these powertrains strongly relies on the energy converter performance, as well as on the energy management strategy deployed on board. In [38] investigates the potential of fuel consumption savings of a series hybrid electric vehicle using a gas turbine as an energy converter instead of the conventional internal-combustion engine. The results show an improvement in the fuel consumption of 22–25% with the gas turbine as the auxiliary power unit in comparison with that of the internal-combustion engine. Consequently, the studied auxiliary power unit for the gas turbine presents a potential for implementation on series hybrid electric vehicles.

Second is Parallel HEV. Both an internal combustion engine (ICE) propels a parallel hybrid and an electric motor connected to a mechanical transmission[39]. Power distribution between the engine and the motor is varied so both run in their optimum operating region as much as possible. There is no separate generator in a parallel hybrid. Whenever the generator's operation is needed, the motor functions as generator[40][41]. In a parallel mild hybrid, the vehicle can never drive in pure electric mode. The electric motor turns on only when a boost is needed[42]-[45].

Aiming at the time-consuming problem of series configuration and the fact that its adaptive energy control management strategy cannot provide the optimal fuel consumption, this paper in [46] proposes highly integrated parallel HEV model The results show that (1) the cumulative fuel consumption obtained from the integrated model is 832.01g while the tested fuel consumption is 845.82g. The relative error between the simulated and tested fuel consumption is 1.63%. On this basis, average fuel consumption of the proposed online energy management algorithm based on Lyapunov optimization is reduced by 13% compared with A-ECMS algorithm, which lays the foundation for the development of a unified algorithm platform.

Hybrid electric vehicle (HEV) technology is an effective way to resolve the problems of energy consumption and air pollution. Energy management strategies are critical to the performance of HEVs. In [47], a novel energy management strategy of equivalent consumption minimization strategy (ECMS)-type is proposed for parallel HEVs based on energy prediction (ECMS-EP) in parallel HEV. The simulation results show that the proposed ECMS-EP is able to achieve more stable SoC trajectories and better fuel economy with a fuel consumption reduction of 2.7%-7% compared with the traditional adaptive-ECMS. In [48] presents a novel real-time EMS, namely fuzzy adaptive-equivalent consumption minimization strategy (Fuzzy A-ECMS), for a parallel HEV. The simulation results show the feasibility and effectiveness of Fuzzy A-ECMS, yielding 0.46% to 5.91% reduction of fuel consumption and more stable SOC charge sustainability compared with the other three EMSs.

In [49] propose an energy-efficient supervisory control method for the power management of parallel hybrid electric vehicles (HEVs) to improve the fuel economy and reduce exhaust gas emissions. Plug-in HEVs ((P)HEVs) have multiple power sources (e.g., an engine and motor) that should be cooperatively operated to meet the required instantaneous traction power for the desired vehicle speed while satisfying their physical limits. Because the efficiencies of the engine and motor vary with different operating speeds and torques, the main issue of energy-efficient power management is to allocate the power demand among the power sources by achieving maximum power conversion efficiencies and satisfy the operating limits. In comparison with the existing charge sustaining strategy and charge depleting and charge sustaining mixed controllers, we recorded fuel efficiency improvements of over 4.8 % and 7.3 %, respectively, in a mixed urban-suburban route. In order to further reduce fuel consumption, a double input and single output fuzzy logic controller has been established for the energy management of a parallel hybrid electric vehicle (HEV). In [50], the fuel economy and battery state of charge (SOC) of vehicles has been numerically investigated. Results showed that compared with the logic threshold control strategy, the fuel consumption under the NEDC and WLTC driving cycles are reduced by 13.3% and 4.5%, respectively, when the fuzzy logic control strategy was adopted. In addition, compared with the logic threshold control strategy, the fluctuation of SOC variation of the fuzzy logic control strategy is much smaller under both driving cycle, which has a positive effect on increasing the effectiveness of the battery discharge, maintaining stability the battery operating, and extending the battery life. In [51] presents a thorough comparative study of energy management strategies (EMSs) for a parallel hybrid electric vehicle (HEV), while the battery ageing is considered. The principle of dynamic programming (DP), Pontryagin's minimum principle (PMP), and equivalent consumption minimization strategy (ECMS) considering battery ageing is elaborated. Simulations are carried out for DP, PMP, and ECMS to analyze their features, wherein results indicate that DP obtains the best fuel economy compared with other methods. Additionally, the difference between DP and PMP is about 2% in terms of fuel economy. The observations from analysis results provide a good insight into the merits and demerits of each approach.

Lastly, the vehicle can be powered by the gasoline engine working alone, the electric motor by itself, or by both energy converters working together. Power distribution between the engine and motor is designed so that the engine can run in its optimum operating range as much as possible [52]-[54]. Series-parallel hybrid electric vehicle (SPHEV) is a compact and effective configuration of HEV, which has great potential to save fuel consumption. Because of multi power sources (one engine and two electric motors) and various driving conditions, it is difficult to design an optimal energy management strategy (EMS). To obtain better fuel economy, a novel particle swarm optimization based (PSO-based) nonlinear model predictive control (NMPC) strategy is proposed in [55] for EMS of SPHEV. First, a nonlinear model predictive control framework is designed. Then, a modified particle swarm optimization is used for receding horizon optimization. Next, in order to realize fast computing, a two-steps optimization method is adopted. Finally, the proposed strategy are verified by simulations based on the data of a real bus and a driving cycle. The results show that the fuel consumption of SPHEV is greatly decreased by more than 10% compared to that with CD-CS strategies. The series hybrid transmission (SHT) and series-parallel hybrid transmission (SPHT) have become an important development direction in the field of hybrid electric vehicles (HEVs) in China discussed in [56]. The results show that the SPHT has notable advantages in fuel saving compared with the SHT, especially in high-speed driving cycles for type C vehicles, while there is a negligible difference in the fuel consumption between the two for type A vehicles under urban driving cycles. Under the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), the SPHT has a fuel saving of approximately 7.2% more than the SHT for type B vehicles. This study provides a new theoretical basis on technical path selection for the SHT and SPHT.

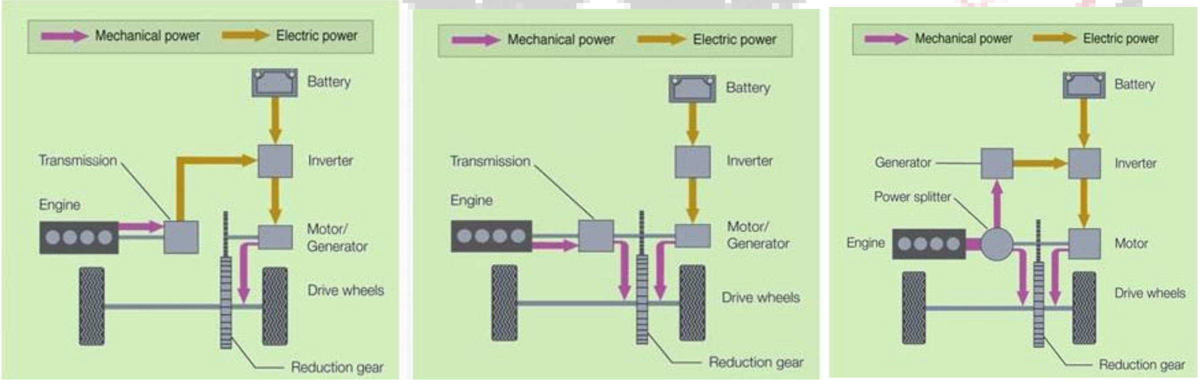

Figure-2 Different Configuration of HEV (a)- Series,=; (b)= parallel; (c)= Series-parallel

Table-2 Comparison of different State-of-Arts on the configuration of HEV

References	**Configu-ration**	**Result**	**Efficiency**	**Complexity**	**Weight (Kg)**	**Size**	**NO_X (g/Km)**	**CO (g/Km)**	**HC**	**FC**
[35]	SH	mean prediction error= 1 m/s	L	L	M	Bulky	M	M	L	M
[36]	SH	fuel consumption= 12.48 % Reduced	L	L	M	Bulky	M 92.64 %	M	L	M

[37]	SH	improvement in the fuel economy by 21%	L	L	M	Bulky	M	M	L	M
[38]	SH	improvement in the fuel consumption of 22–25%	L	L	M	Bulky	M	M	L	M
[46]	PH	fuel consumption is 845.82g	M	M	L	Moderate	L	L	M	M
[47]	PH	a fuel consumption reduction of 2.7%-7%	M	M	L	Moderate	L	L	M	M
[48]	PH	0.46% to 5.91% reduction of fuel consumption	M	M	L	Moderate	L	L	M	M
[49]	PH	fuel efficiency improvements of over 4.8 % and 7.3 %	M	M	L	Moderate	L	L	M	M
[50]	PH	driving cycles are reduced by 13.3% and 4.5%,	M	M	L	Moderate	L	L	M	M
[55]	SPH	fuel consumption of SPHEV is greatly decreased by more than 10%	H	H	L	Small	L	L	L	L
[56]	CH	fuel saving of approximately 7.2%	H	H	M	Small	L	L	L	Lo

*SH= Series HEV, PH= Parallel HEV, SPH= Series/ Parallel HEV, CH= Combine HEV, L= Low, M= Medium, Lo= Lowest

IV. IMPORTANCE OF BATTERY SOC PREDICTION

Precise prediction of the State of Charge (SOC) in Electric Vehicle (EV) batteries plays a pivotal role in various operational and management aspects of EVs. Its primary importance lies in estimating driving range, enabling drivers to gauge the distance they can cover before the necessity of recharging arises, thus reducing concerns over limited range. Equally important, SOC prediction is integral in tracking the health and lifespan of the battery. Regular monitoring of SOC helps in evaluating the battery's condition over time, guiding decisions related to maintenance or replacement. Additionally, it assists in optimizing charging cycles, a key factor in extending battery life and ensuring its efficiency, while also avoiding detrimental practices such as overcharging or deep discharging.

SOC prediction also enhances overall vehicle performance by effectively regulating power systems, including processes like acceleration and regenerative braking. In the realm of energy management, particularly for EVs equipped with regenerative braking, accurately predicting SOC is essential for the effective capture and storage of energy during braking phases. This aspect becomes even more crucial for EVs that support vehicle-to-grid (V2G) technology, as it helps in determining how much energy the vehicle can contribute back to the power grid, aiding in its stability.

Furthermore, SOC data is critical for effectively planning and timing charging sessions, an aspect that gains importance in scenarios like fleet management or the use of communal charging stations. Finally, the provision of reliable SOC information significantly enhances consumer trust and satisfaction, promoting wider acceptance and adoption of EV technology. In essence, SOC prediction is key to ensuring that EVs are not only efficient and safe but also viable alternatives to conventional vehicles, thereby boosting their functionality and attractiveness.

V. CONCLUSION

The increasing environmental issues caused by traditional internal combustion (IC) engine vehicles have led to a shift towards EVs, which offer a cleaner, emission-free service. However, EVs face challenges in driving range, battery state of charge prediction and infrastructure. HEVs provide a solution to these challenges by combining electric and internal combustion engines. They use both engines either simultaneously for enhanced power and torque or separately, depending on the driving conditions. The electric motor in HEVs is supported by a rechargeable battery, allowing for electric-powered driving. The article examines the latest advancements in HEV technology, the factors driving its development, the challenges faced, and innovative manufacturing solutions proposed by researchers and the automotive industry.

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